Noname manuscript No.
(will be inserted by the editor)

Physical Analysis of Handshaking Between Humans

Mutual Synchronisation and Social Context

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Received: date / Accepted: date

Abstract One very popular form of interpersonal interaction used in various situations is the handshake (HS), which is an act that is both physical and social. This article aims to demonstrate that the paradigm of synchrony that refers to the psychology of individuals' temporal movement coordination could also be considered in handshaking. For this purpose, the physical features of the human HS are investigated in two different social situations: greeting and consolation. The duration and frequency of the HS and the force of the grip have been measured and compared using a prototype of a wearable system equipped with several sensors. The results show that an HS can be decomposed into four phases, and after a short physical contact, a synchrony emerges between the two persons who are shaking hands. A statistical analysis conducted on 31 persons showed that, in the two different contexts, there is a significant difference in the duration of HS, but the frequency of motion and time needed to synchronize were not impacted by the context of an interaction.

Keywords Handshake · Synchrony · Data Glove · Gesture · Physical interaction · Temporal Movement Coordination

1 Introduction

The consumer expects from the humanoid robot all that he sees in the media. Hollywood produces an attractive picture of a humanoid robot that is able of reproducing a lot of behaviors identical to the human being: I robot, Ex Machina, Chappi,... However, the humanoid robot is not able to reproduce the ensemble of behaviors produced by a living creature. Individual's gestures, behavior, and appearance are difficult to mimic in the actual state of technologies and material.

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The industry is not capable to produce a humanoid robot that corresponds to our expectations, delivered through a medias.

Humanoid robot skills are improved by researchers for some models of robots [53,33,28,46]. Not only the performance of motion characteristics demands of enhancement but also general robot appearance for sufficient robot acceptability [49,13,15,40,35]. Humanoid robot gestuality is an important feature. As shown by Salem et al. [58], a robot presenting social cues in the form of the co-verbal hand and arm gestures are perceived in a more positive way than a robot whose sole means of communication is limited to a single modality. The striving of researchers to move robot towards being cooperative and social via greeting and communicating behavior with people has a lot of success [66,39,51,60].

For humans, physical and social interpersonal interactions induce gestural and verbal/non-verbal communications based on rhythmic mechanisms and rhythmic movements. These mechanisms could play a fundamental role in physical and social interpersonal interactions [72,65] and could be an emergent feature of the physical and social interactions between humans who adapt to each other and learn from each interaction, generating synchronization phenomena of movements and creating conscious or unconscious links between people [14]. Thus, distinct individuals can spontaneously enter into interaction and successfully perform coordinated actions through an exchange of information by means of their sensorimotor, cognitive and social underpinnings. Despite numerous research [43,7,26,1,21] were synchrony is considered to improve the robot learning, there is no investigation of the key feature of physical interaction as synchrony and its temporal-frequency characteristics in human-robot contact communication. Little is known about how synchrony impacts the physical interaction between the robot and human, as most previous studies in this vein have focused on motion properties improvement [54, 47]. Our work aims to fill the gap via analysis of synchrony of physical interaction between humans.

In interpersonal gestural rhythmic movements, handshaking has an important and universally social function because it regulates and maintains human interactions [59,24,8,18]. It is a multimodal physical interaction, socially common but complex from a neuroscience and robotics point of view because it involves fine and complex coordination which engages the body and gaze throughout the act: from the preparation to the contact, the locking, the rhythmic and synchronized movement until the withdrawal of the hands [68]. Therefore handshaking can be considered as a paradigm for social and physical interactions, in particular because its multimodality is based on physical and social acceptance of rhythmic movements. The idea that a robotic device serves as the medium of the handshake between two people was considered firstly in [25,50]. The handshake between a human and robot was examined in the fullest and deepest form in the work of Jindai and his group over the past twelve years [32,29,71,30,31]. Turing test were performed for handshake [36] and has been improved the behavior of the robot performing handshake [5]. Different types of robot's controller are presented for online adaptation of motion dynamics [52] and the strength of synchronization [70], for motion imitation [17].

However, handshake (HS) is a complex act, requiring a fine coordination between the partners movements with strength and grip, and giving rise to prototypical motor patterns that may be associated with specific psychosocial content felt during the interaction [4,3,10]. HS is widely used in marketing and management contexts [62]. Regarding the accuracy of the first impression, conscientiousness is better identified when the group of 25 subjects shake hands than when they do not [8]. Clinical observations shown that HS is an indicator of health [69, 61]. The performance of the HS task requires a complex orchestration of muscle forces, joint motions, and neural motor commands in service of an interpersonal communication goal. This complex orchestration is often referred to as a coordinative structure or functional synergy [67], and is organised in direct relation with an information-rich environment. The behavioral patterns of such synergies can be controlled and modelled by a system of coupled nonlinear oscillators [23, 22] having learning properties [57] and capturing and learning parameters of interaction [47]. In other words, during HS, different body segments display the same patterns of coordinated movement described by a system of coupled oscillators. The communicative functions of HS behaviour were observed as a function of social context, interpersonal intimacy, and gender. According to Huwer [27], the context of the interaction strongly influences the duration of the HS between humans. According to Huwer [27], there are six different social contexts, for a handshake. Consolation and congratulatory duration are longer than hello, farewell/thank you, and agreement contexts that appear to produce essentially shorter handshake duration. Actually, we did not test any other social contexts than consolation and greeting. These two contexts were considered only, because they demonstrate extreme handshaking duration, i.e., long for consolation and short for greeting. The work presented in this article explores the paradigm of synchrony in HS. The physical features of HS between humans are investigated within two different social contexts: greeting and consolation [27]. The contribution of this article is twofold. First, we measured and analysed the primary physical parameters of the HS gesture between humans within these two simple social contexts. Second, we highlighted the emergence of synchrony during the HS.

1.1 Hypotheses

In this article, the following hypotheses are retained regarding the relations between HS dimensions:

- Hypothesis 1: The dimensions of the HS can be better discriminated in two social contexts and different gender associations [27]. Investigated dimensions are the duration and the frequency of acceleration of the hand for two social contexts and for different gender associations. The null hypothesis H_0 is that there is no difference in the means of HS duration for two social contexts in the studied population.
- Hypothesis 2: The synchronization time neither depends on the social context nor on different gender associations. Investigated dimension is time between the start of a handshake and the onset of hand movements synchronization. The null hypothesis H_0 states that there is no difference between synchronization time for two social contexts and different gender associations.
- Hypothesis 3: The force of hand grip does not depend on the social context or different gender associations. The investigated dimension is the strength of the grip. The null hypothesis H_0 states that there is no difference in the mean forces between two social contexts and different gender associations.

2 Materials and methods

2.1 Participants

Two graduate students (one man and one woman) served as experimenters and were trained as HS coders in this study. They were blind to the hypotheses about the relation between handshaking characteristics and synchrony. Thirty-one undergraduate students participated in the experiment (19 males, 12 females, age range: 19-22, mean age: 21.5, SD: 0.98). Each subject was recruited by telephone or by personal invitation from the researcher (first coauthor). The subjects were unknown to the researcher and the behaviour coders at the time of the investigation. We randomly grouped the subjects into 31 dyads (5 female dyads, 19 male dyads, and 7 mixed gender dyads). During five days of the study we invited five or seven students per day.

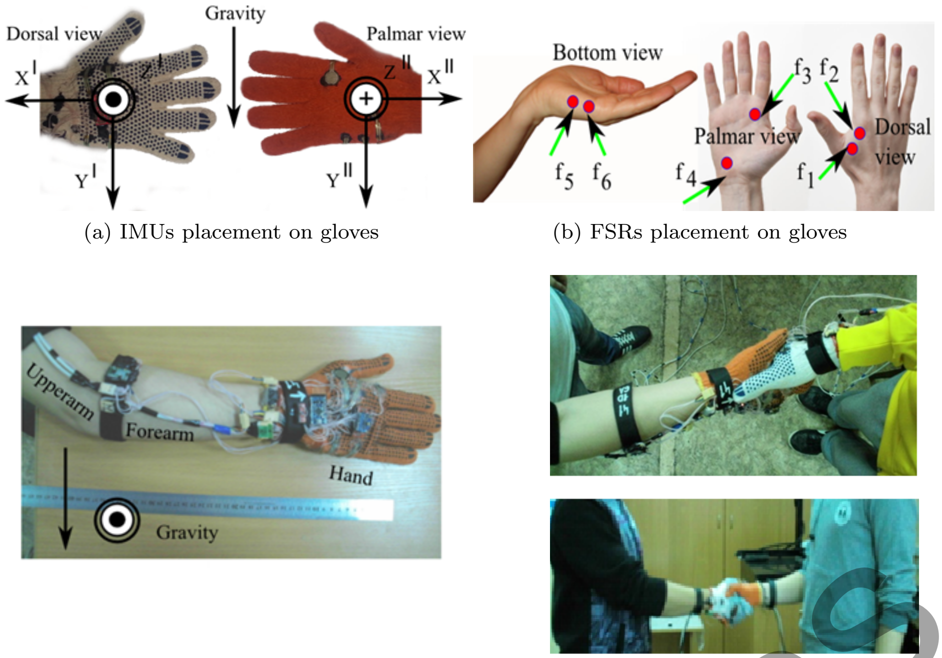
2.2 Motion and force capture system

To measure the HS parameters, we built a data glove prototype instrumented with inertial measurement units (IMU) [48]. These sensors are accurate, inexpensive, and portable and allow long-term recordings in clinical, sport and ergonomics settings. Comparing to optical motion analysis systems body-mounted IMUs give results that are very close to those of the Vicon system (i.e., small standard deviations [45]), along with a large coefficient of multiple correlation [34]. One data glove was proposed for each member of the dyad. Data glove consists of a tri-axial accelerometer and a tri-axial gyroscope attached to it in aims to be at the back of the hand when the glove is worn Fig. 1a. Six force-sensitive resistors placed on each data glove on the palmar and dorsal surface of the of the glove to maximize the information about the fullness of the grip of two interacting hands Fig. 1d. The forearm of the subject was instrumented with two accelerometers: at the beginning of the forearm (elbow joint side) and at the end of the forearm (carpus proximity) Fig. 1b. The architecture of a proposed handshaking measurement system is based on a 16 MHz microcontroller ATmega2560 for simultaneous acquisition of data from both gloves. Motion and force sensors data was collected at 50 Hz.

Proposed wearable sensor architecture allows conducting reproducible experiments to quantify HS parameters such as duration, frequency of acceleration of the hands and handgrip strength. The beginning and the end of the HS, and the handgrip strength are defined by force sensors measures.

2.3 Experimental procedure

Each subject was informed that the primary purpose of the study was to perform several sensory-motor tests taking approximately 30 minutes and that they would receive a small fee for participation. When the subjects arrived at the laboratory, the researcher (first coauthor) explained to each participant about the objective of the experiment. The experiment comprised several experimental conditions according to [27] that were defined to the participants, as follows:



(a) IMUs placement on gloves (b) FSRs placement on gloves

(c) IMUs placement on the forearm (d) The hansshakers

Fig. 1: Data gloves with the local coordinate system of accelerometers and array of six force-sensitive resistors for placement on the forearm. Superscripts I and II are introduced to distinguish the two subjects.

- Greeting context. Each participant was asked to greet the encoder by shaking hands with him: You have just arrived at a meeting, and everyone is greeting one another.
- Consolation context. Your partner has just lost someone s/he loved and is feeling down. Offer a HS in consolation.

Subjects were asked to perform a series of five consecutive HS in each context with a pause between them. No communication took place between the participants other than the greeting. For one dyad, the experiment lasts on average 16 minutes. This time includes an explanation of the purpose of the experiment, the instrumentation of the participant, the calibration of the measuring system, handshakes registration and the removal of the set of sensors. The HS was recorded with photos of the dyad and with the results of the Big Five Personality Test [19] to form a data-set. During the experiment, the coders received the following instructions: to perform a natural HS, do not stop the rhythmic movement of your own hand before the tested subject stops the movement. The coders had a resting period of at least 10 minutes between two successive trials.

2.4 Preliminary analysis of HS between humans

Two subjects wore data gloves and completed all calibration tests (see [38] for more details). The people were at a sufficient distance so as not to make further movements in space during the test. A typical example of the parameters measured by our instrumented data gloves is depicted in Fig. 2. The accelerations of the subjects' hands overlap in the same timescale. Fig.2a depicts the acceleration from the x-axis of the accelerometers (sagittal plane); Fig.2b and Fig.2c depict the accelerations on the y- (sagittal plane) and z-axes (frontal plane), respectively. The accelerations show that the main movement occurred in the sagittal plane. Indeed, the acceleration values along the x- and z-axes should be modified by considering the rotation axis during the movement (this rotation is not corrected); thus, these accelerations are low compared with the acceleration along the y-axis. We have completed the measurements of the acceleration of the hand with the acceleration of the forearm (the first sensor is near the wrist and the second sensor is near the elbow joint). Comparing the obtained data, we concluded that the signal from the hand-mounted accelerometer is better for the handshake quantification, being in the range from $\pm 2g$. Therefore, for further movement analyses, we use the y-axis acceleration as the information that best expresses the strength and dynamics of the HS, and it will also be used to analyse the synchrony phenomenon.

The typical results in Fig. 2 show that the interaction consists of four phases. In phase 1, the start of handshaking (SoH) subjects bring their hands forward to shake. In phase 2, physical contact (PhC) is established, and the participants are in the initial stage of physical interaction. The synchronisation of their movements is unconsciously beginning. In phase 3, mutual synchronisation (MS), the movements are synchronised between the two hands. The phase 4, end of handshaking (EoH), represents the end of physical contact; the hands then move to the subjects bodies, and they pause before another HS.

The analysis of the measures from the array of force sensitive resistors allows delineation of the contact duration of the HS. The rising of the signal from force-sensitive resistors defines the start of contact between the hands (t = 8.6 s), and the falling of signal defines the end of the contact (t = 11.3 s). Fig.2d shows the forces from the sensor array on the glove of the first subjects hand (sensors $f_1^I \dots f_6^I$), and Fig.2e shows the forces measured on the hand of the second subject (sensors $f_1^{II} \dots f_6^{II}$). We can observe sine profiles of force pattern during the contact and its value variation with up/down motion and decrease at the end of the HS. Fig. 2k shows the mean values from the six force sensors during the same HS for the first (f_m^I) and second (f_m^{II}) subjects.

The analysis of the acceleration patterns indicates that the approach phase (SoH) occurs in the time interval [8.0 8.6 s] before the physical contact, as confirmed by the force sensors. Then, from 8.6 to 9.6 s, the subjects physically interact (PhC), and their movements start to synchronise. In the next phase, from 9.6 to 11.3 s, we observe the stability of the rhythm and synchrony of the HS movements (MS). The HS ends (EoH) as soon as the two subjects terminate the physical contact between their hands and move their arms freely toward their own body (t = 11.3 s). The end of the HS is confirmed by signals from the force sensors on the glove. The duration of this particular HS is 2.7 s, with maximum acceleration values up to 2 g.

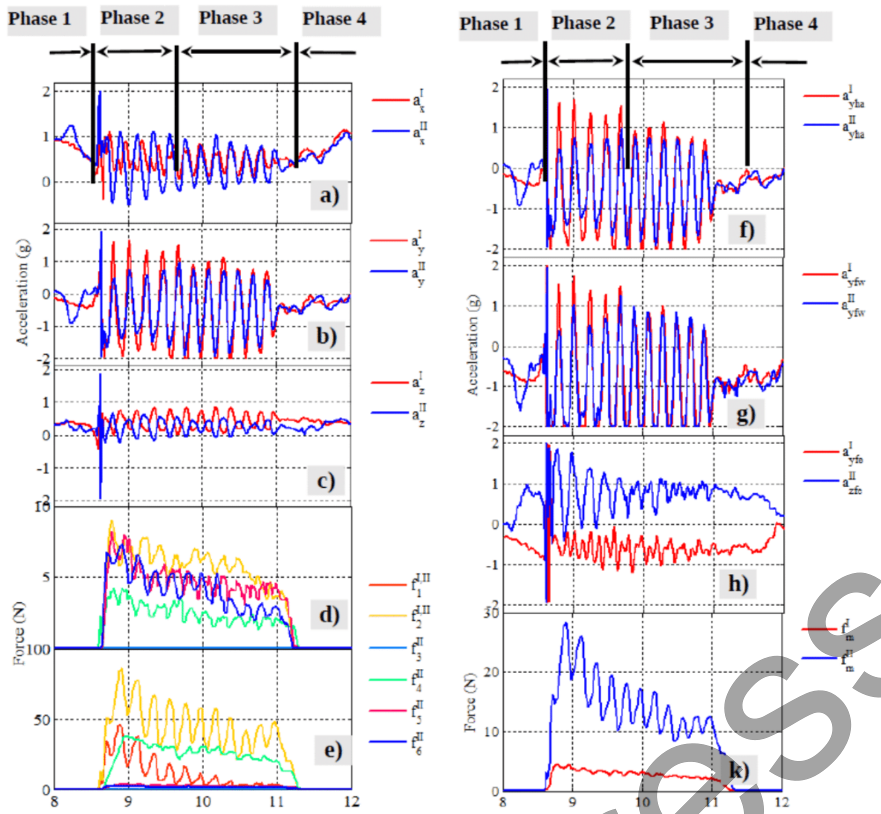


Fig. 2: HS acceleration pattern according to the local coordinate system and forces measured during HS. Four phases of HS are delineated.

2.5 Synchrony quantification of HS

Synchronicity between the two signals is an emerging phenomenon, and it carries an important signature of the behaviour during the interaction. That is why calculations of some index must quantify the synchrony. To achieve this, the phase-locking value index (PLV) is used to calculate the phase difference between the accelerations of two human hands. The PLV is a method to detect the synchrony in a frequency band of EEG signals [38]. The PLV is obtained after filtering and applying a convolution with a complex Gabor wavelet to the two signals (see [38] for more details). If the PLV value is close to one, this means that the signals are synchronised; and, if this value approaches zero, the signals are unsynchronised. In our experiments, the PLV was defined by

$$PLV_{I,II} = \frac{1}{N}\sum_{t=1}^{N} exp(i(\theta_I - \theta_{II})) \tag{1}$$

where θ_I and θ_{II} are the phases of the accelerations $a_y^I(t)$ and $a_y^I I(t)$ measured on a person's hand (Roman numerals stand for subject number). The member

$\theta_I - \theta_{II}$ is the phase difference between the two signals, and N is the number of samples. The parameters of the PLV computing are fixed for the analysis of natural arm movements in accordance with the work presented by Lachaux et al. [38]. The simulation of the PLV using two sine signals, one with a frequency of $f_1 = 1$ Hz, and the second with a multiple frequency $0.2 < f_1 < 2$, shows that the PLV calculus allows faithfully evaluating the synchronisation if $0.6 < f_2 < 1.5$, which largely surrounds the frequency ratio of the movements we analyse.

2.6 Frequency analysis of HS

For an overall analysis of HS pattern, we used fast Fourier transform (FFT) [16], which is a conventional spectral analysis method to compute the frequency components of a signal, and we examined its dominant frequencies. Fourier analysis has long been a standard tool describing the overall regularity of a signal, and it copes perfectly with the sinusoidal signals. The FFT does not provide the time at which these frequency components occurred. Thus, a more comprehensive tool is required that can analyse the accelerometer signal in more detail (in both time and frequency). For a detailed analysis of HS pattern, we used synchrosqueezing as a tool to extract and compare oscillatory components of a non-stationary physical signal with sharp high-frequency transients [12,63]. This tool provides a powerful method for analysing signals with time-varying behaviour, such as an HS acceleration pattern, and can give insight into the structure of their constituent components. In this article, for overall analysis and hypothesis testing, we used results of FFT only. The results obtained by the synchrosqueezing method were used only to visualise changes in the frequency of the HS during the time.

2.7 Statistical analysis

Statistical differences in HS duration were analysed by mean of a Cox regression, also called a Cox proportional model [11]. In the model, both the condition and the type of couple were taken into account as fixed effects. Since the experiment was based on two measures performed on the same individuals, the variation between them was added as a random effect in a mixed model. Frequencies, on the other hand, were analyzed with a linear mixed model for Gaussian traits using the same framework. Computation were done in the R, version 3.4.3 [55] with the 'coxme' [64] and the 'lme4' packages [6]. Significant effects were tested using standard likelihood ratio tests.

3 Results

3.1 Analysis of HS during greeting

A typical example of a HS during greeting, with physical contact phase 0.5s, is shown in Fig. 3a. In this figure, one can find three different phases without mutual synchronisation in the pattern of hand acceleration: SoH (15.5s - 15.95 s), PhC (15.95 s - 16.5 s), and EoH (16.5 s - 17 s). The PLV is approximately 0.5, indicating

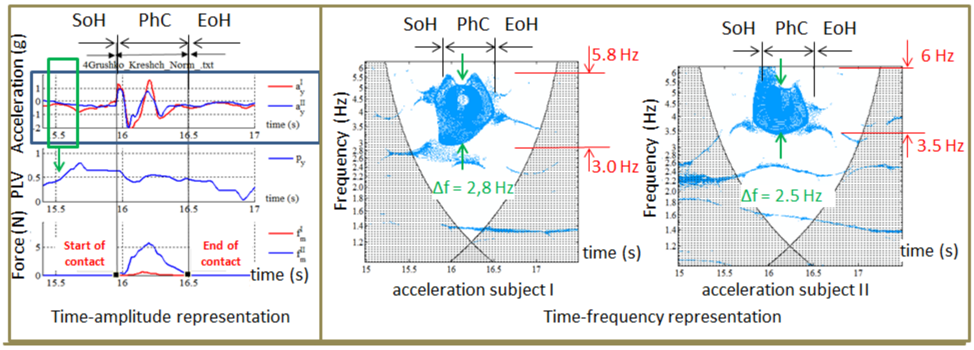


Fig. 3: An example of a HS in greeting: a) time-amplitude signal representation and average forces exerted by each subject; b) time-frequency signal representations (in synchrosqueezing Toolbox, the frequency axis is on the log scale, and the boundary conditions are rejected by padding the gray grid on both sides of the signal). The blue zones correspond to the power spectrum founded in the HS acceleration pattern.

a lack of synchrony. This means that the couple fails or refuses to synchronise the movements of their hands perfectly during this physical interaction. For the SoH phase, the synchrosqueezing analysis shows that there was no dominant frequency except a narrow band of frequency centred on 2.8 Hz for the first person and 2.2 Hz for the second person, which corresponds to the preparation of arm motion without contact. The PhC phase represents a wide band of 2.8 Hz centred on 4 Hz for the first person and a band of 2.5 Hz centred on 4.5 Hz for the second person. The wideness of the band could be interpreted as a search, by the two subjects, for a common motion frequency to pass into the synchronous mode, but the social context did not assume the long duration of an HS. The subjects stop their hand grasp without reaching a synchrony. During the PhC, the forces exerted by the two persons are different. One subject presses the hand more strongly than the other. The force analysis shows that the first subject experiences a force of approximately 5 N, and the second subject hand is gripped with a force of 1 N. The force did peak in up-motion, and decreased at the end of the HS. Another example of a HS in Greeting context is shown in Fig. 4. Contrary to the previous example, this HS was longer (duration of the physical contact is 1.25 s), and the dyad produces synchronised movements (PLV = 1), including an MS phase from 17.2 s to 17.5 s. In this case, one can find the four phases, including an MS phase from 17.2 s to 17.5 s, and a transient phase between MS and EoH, like a physical contact phase but after the synchrony. Its duration will be examined in the discussion section. This behaviour included in MS duration can be explained by a lack of attention during the HS. We do not know the exact origin of this phenomenon, but we assume that one of the persons lost her/his attention to coordinate the motion or did not had any desire to continue the HS, but the other partner continued the hand grip. From the point of view of the movement dynamics, in the time interval (17.5 - 18.0 s), the time-frequency graph for the first subject has a narrow bandwidth; but, for the second subject, this graph has a wider bandwidth centred on 3.8 Hz. The synchrosqueezing analysis confirms that subject *I* continued his

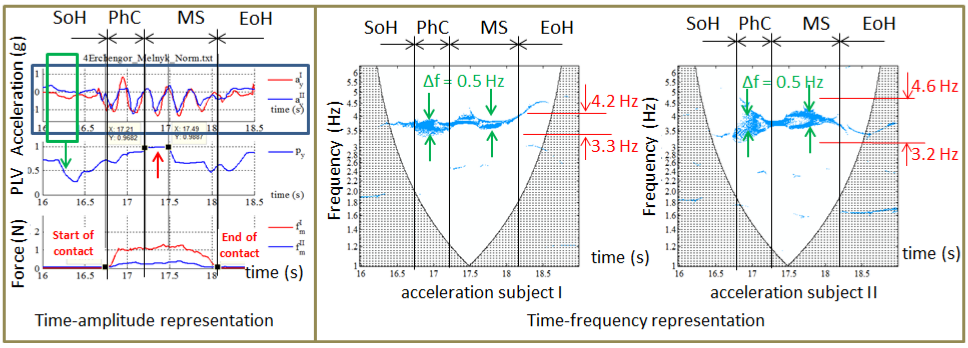


Fig. 4: Example of another HS during greeting, which is longer than the HS in Fig. 3 and with MS phase: a) time-amplitude signal representation; b) time-frequency signal representations.

motions with a stable rhythm, and subject *II* had a polyharmonic rhythm due to the weak force he exerts on the hand of subject one. The synchrosqueezing analysis of the hand accelerations for the PhC phase (16.7s-17.2s) shows for the first person a narrow band with a larger frequency of 0.1 to 0.5 Hz, depending on the phase, and centred at approximately 3.8 Hz. For the second person, the bandwidth is larger in PhC (1.4 Hz) but similar during the rest of the HS. The bandwidth is narrower during MS (0.2 Hz) and centred on the same central frequency of 3.8 Hz. The PLV calculation confirms the mutual synchrony (MS). Indeed, an analysis of the third subfigure shows that person I shook hands with a force of approximately 0.25 N, but he experienced a force from individual II of approximately 1N. Subject I applied a larger force to subject II, which made his wrist rigid, contrary to that of subject II, whose wrist was more flexible due to the lower force and is exerted on the hand of subject I. The flexibility in the wrist generates several oscillations at different frequencies. We can see that the force does not vary with up/down motion but decreases at the end of the HS.

3.2 Analysis of a consolation HS

An example of a Consolation HS with a physical contact of 0.6s is presented in Fig. 5. The synchronisation occurred after 0.6s (before the interaction, the value of PLV was 0.5) and was maintained until the end of the interaction. The four phases (SoH, PC, MS, and EoH) are present. The frequency analysis of the hand acceleration for the PhC phase in time showed a weak power spectrum density approximately 4 Hz. The MS phase has a narrow frequency bandwidth from 0.05 to 0.1 Hz that varied synchronously. Comparing the PLV and the change in the spectrum, we conclude that the hand movements were synchronous, and despite the smooth oscillation spectrum, the PLV remained stable. We can see that the force pattern reflects the periodic character of acceleration and varies with up/down hand motion, but decreases along the duration of the HS. Another example of the consolation HS is shown Fig. 6. Contrary to the previous example, this HS was shorter and close to the Greeting HS (duration of the physical contact is 1.25 s),

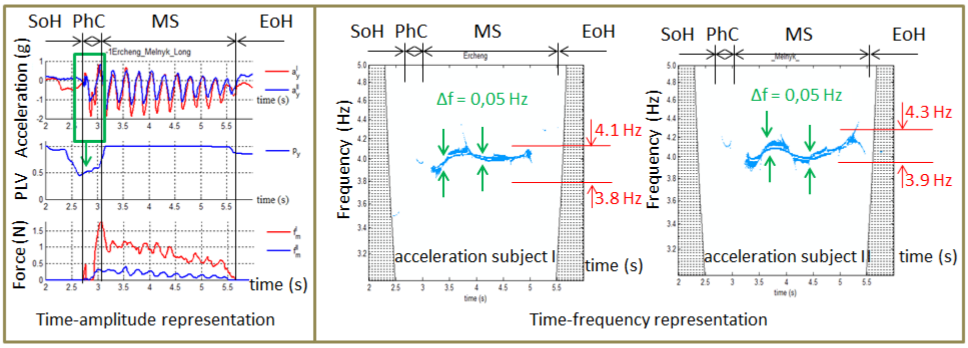


Fig. 5: An example of an HS with MS phase in consolation social context: a) time-amplitude signal representation; b) time-frequency signal representations.

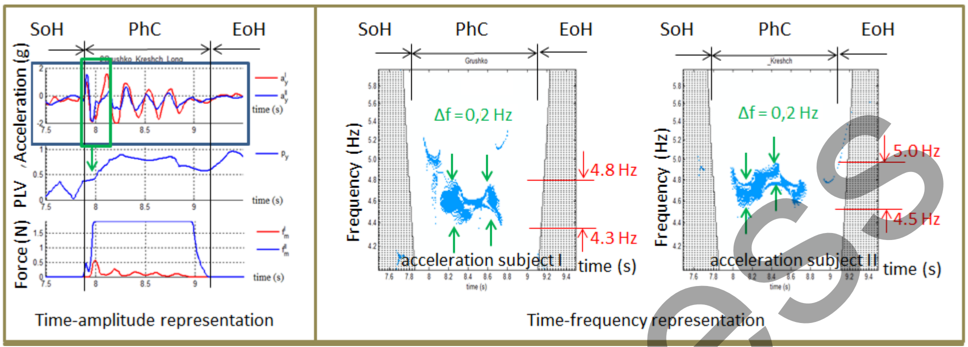


Fig. 6: Example of another HS with quasi MS phase in consolation social context: a) time-amplitude signal representation; b) time-frequency signal representations.

and the dyad does not produce synchronised movements. In this case, one can find the three phases (SoH, PC, and EoH). The time-frequency representation shows that spectrum of HS pattern is wide (Δf = 0.2 Hz) compared with the previous case.

3.3 Duration and strength of HS

The normality test of Kolmogorov-Smirnov [37,44] with Lilliefors correction [41] were performed on each dataset of the HS duration without gender difference. It shows that the distribution is not a standard normal one (Gaussian). As shown in [56], physiological data can fit the lognormal distribution and at the same time may not fit it. Due to the communicative function of an HS, the gesture duration and the prosodical and cerebral activity of the human being [42,9], obtained data follow the lognormal distribution. The lognormal distribution is skewed positively, causing the population's mean to be greater than the median. The most common parameters for describing a lognormal distribution is the mean and variance. For the Greeting HS, the mean value is 1.25s (median is 0.89s) (Fig. 7a). For the Consolation HS, the mean value is 2.99s (median is 2.57s) (Fig. 7b).

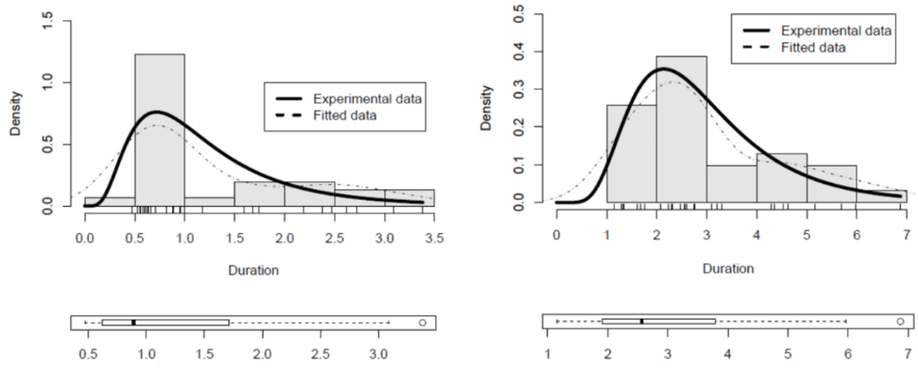


Fig. 7: The probability distribution of experimental data fitted to log-normal law for HS duration in context of greeting (a) and consolation (b).

When gender was considered (Tabl. 1), female/female dyad (FF) had longer handshake duration than did male/male dyad (MM) for both investigated contexts. Mixed dyads (MF) has similar duration to MM dyad in Consolation context, but for Greeting context the HS duration for mixed dyads is close to FF dyad. Handshake grip strength is given in (Tabl. 1). Measured force during the handshake is averaged for simplicity. The analysis shows that there is no significant difference between social contexts and gender differences.

Table 1: Gender differences in handshaking duration (s) and hand grip force (N) for two social contexts

	Duration		**Hand grip strength**	
Dyad gender	Consolation	Greeting	Consolation	Greeting
MM	2.40(0.23)	0.73(0.08)	6.08(1.04)	6.02(0.99)
MF	2.54(0.42)	1.48(0.4)	6.18(0.97)	5.68(0.80)
FF	4.05(0.53)	1.95(0.26)	6.29(0.85)	5.53(1.17)

3.4 Frequency of HS

The approach from the previous subsection was applied to the HS frequency data from 31 dyads, including 310 values (31 couples in two contexts realised five HS). The first step of this analysis is shown in Fig 8 for three HS. The experimental data of a hand's accelerations during HS was used to plot the spectrum for each dyad. The frequency corresponding to the maximum value of the amplitude spectrum is manually extracted for each HS, as shown in the figure. In the second

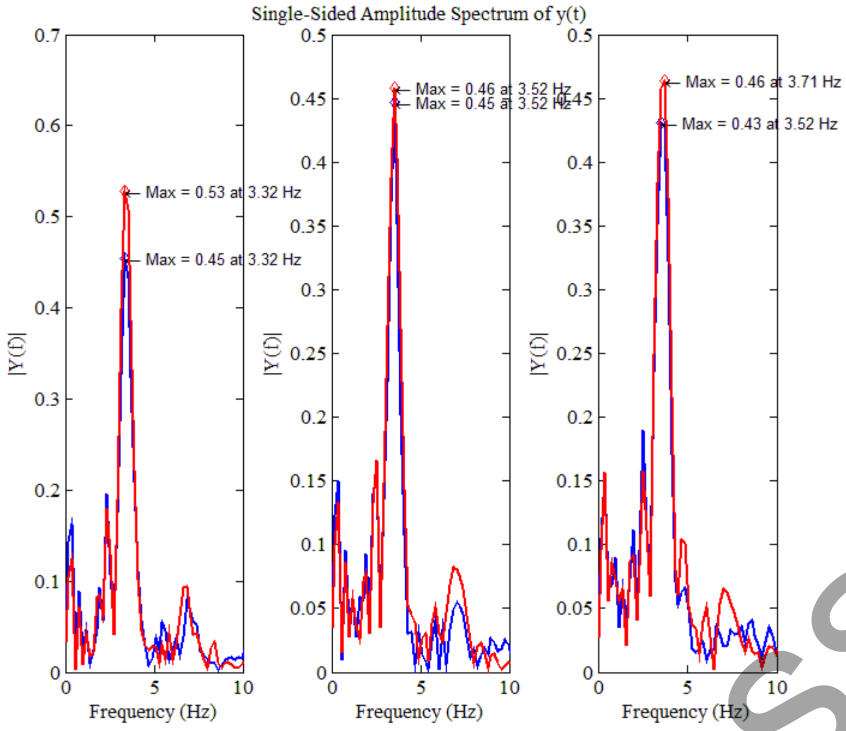


Fig. 8: Spectra of hand accelerations of the first subject (red colour) and second subject (blue colour) for three HS in Consolation context

step, the data of 31 couples were separately analysed for two social contexts. The normality test of Kolmogorov-Smirnov with Lilliefors correction was performed on each dataset of the extracted mean values of HS frequencies. The datasets are not following the normal distribution ($p \leq 0.001$). This means that parametric tests are not applicable to hypothesis testing. For the HS in Greeting context, the average frequency is 3.6 Hz with a median at 3.5 Hz, and for the HS in Consolation context, the mean value is 3.7 Hz with the same median at 3.5 Hz.

3.5 Synchrony phenomenon in HS

For obtained acceleration pattern we introduce the notion of a normalised frequency f_n that corresponds to the median of the data obtained from the statistical analysis ($f_n = 3.5$ Hz) and normalised period τ_n. We calculate how many HS include a PhC-phase duration (averaged from five HS in dyads) that is less than that of the normalised frequency and its multiple frequencies. The graph in Fig. 9 shows that, for a HS in Greeting context, 58 % of the dyads synchronised hand movements during the first normalised period of a HS, whereas 35 % of the dyads synchronised after the second normalised period. Thus, 93 % synchronised their

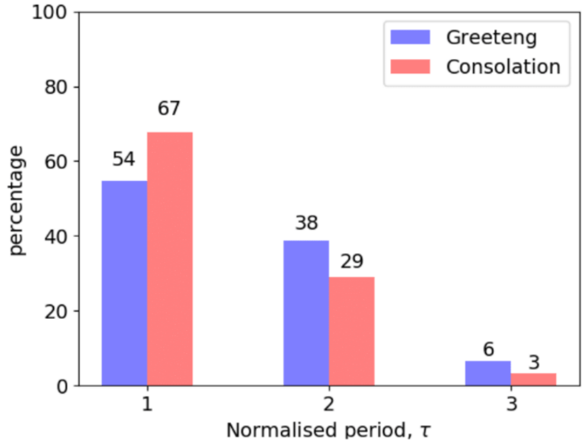


Fig. 9: Dyads that reach synchrony during four normalised periods.

movements during the first two normalised periods of a HS. For a HS in Consolation context in the same population, 70 % and 26 % of the dyads synchronised their hand movements during the first and second normalised periods, respectively.

3.6 Hypothesis testing

3.6.1 Hypothesis 1.

There was a strongly significant difference between the two social contexts ($\chi^2 = 49.11, df = 1, p < 0.0001$) and between the different gender associations ($\chi^2 = 11.44, df = 2, p = 0.003$) regarding the HS duration (Fig. 10a). This underlines the social context impacts on the duration of the human HS. There was a barely significant difference between the two social conditions compared ($\chi^2 = 3.99, df = 1, p = 0.045$) but not differences between the different association types ($\chi^2 = 1.2856, df = 2, p = .5258$) (Fig. 10b).

3.6.2 Hypothesis 2.

In the studied population, the synchronisation time does not depend on the social context of the phenomenon ($\chi^2 = 0.08, df = 1, p = 0.7769$) and no differences were observed between the different association types ($\chi^2 = 1.3926, df = 2, p = 0.498$) (Fig. 11a).

3.6.3 Hypothesis 3.

The force of hand grip does not depend on the social context of the interaction ($\chi^2 = 2.459, df = 1, p = 0.1169$) and no difference was observed between the different association types ($\chi^2 = 0.4609, df = 2, p = 0.7942$) (Fig. 11b), which

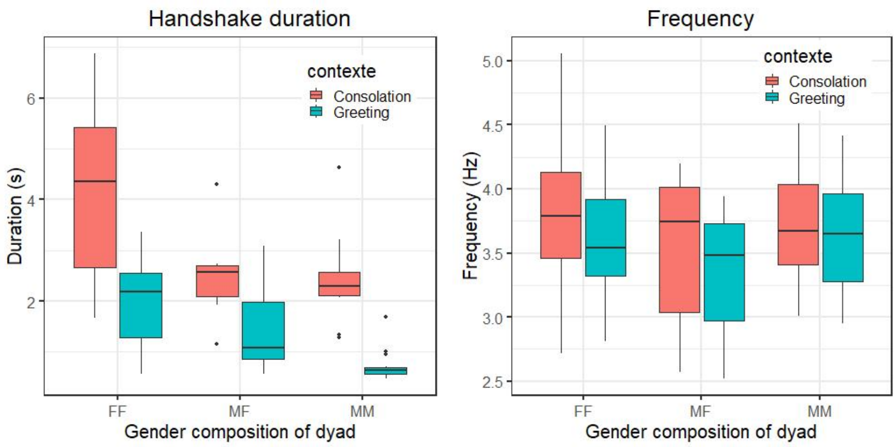


Fig. 10: Hypothesis 1 about the dimensions of the HS in two social contexts (FF stands for female/female dyad, MM stands for male/male dyad and FM for female/male dyad).

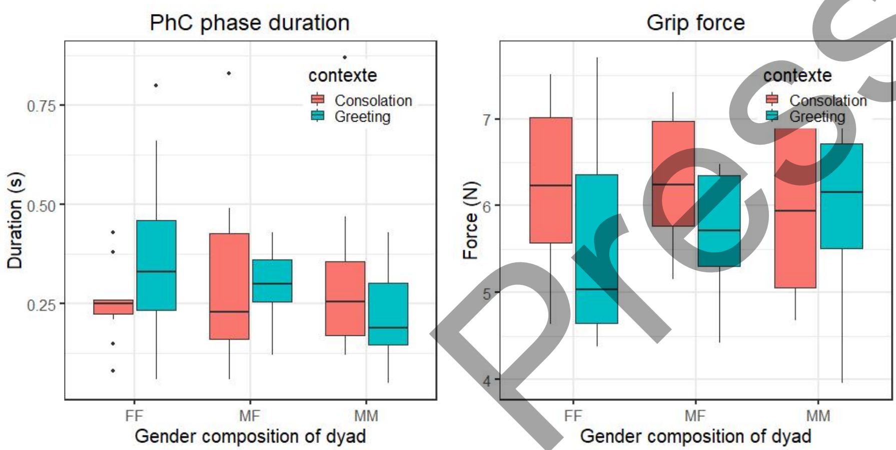


Fig. 11: Hypotheses 2 and 3 about relation in HS grip force and PhC duration.

underlines that the synchronisation occurs independently from context. It is interesting to see the relationship between the force of hand grasp and PhC phase duration. There is no correlation found (p = 0.0075) between force value, and PhC-phase duration shows that the largest force of hand grasp does not induce faster synchronisation of hand motion during the HS between humans.

4 Discussion

In this article, the quantification of the synchronisation of the hand acceleration pattern during a HS between individuals is highlighted using signal processing

tools. The experimental protocol defines a series of five HS for two different social contexts: Greeting and Consolation. We propose to distinguish four phases in the HS motion. The criterion PLV is used to highlight the synchrony phenomenon in the HS (MS phase). For some dyads, there is a long PhC for the first and second HS; but for the next HS, PhC decreases and MS increases. These results show that the last HS in trial starts with a synchronous motion almost at the beginning. We can observe the apparition of synchrony or its elongation from the first to other HS performed in the same dyad, we suppose, meaning a partner social recognition phenomenon (i.e., there is no unknown person behind the subject).
Without gender differentiation, the mean duration for a greeting HS is 1.25 s, and it is 2.99 s for a consolation HS. Gender differentiation shows that duration for FF dyads is bigger for both studied contexts comparing to MM dyads. But for mixed dyads this observation was not confirmed, in the context of the greeting the duration of the FM dyad's handshake is close to MM, and in the context of consolation, it is close to FF.
We use the classical approach of frequency analysis to find the fundamental frequency of phenomenon, and the synchrosqueezing approach to observe the variations of the frequency in time. The synchrosqueezing enables the complete time-frequency decomposition of a noisy and nonstationary HS acceleration pattern. During the HS, the frequency of the hand acceleration pattern varies from dyad to dyad, but the median value stays equal to 3.5 Hz for the two contexts of the HS. Therefore, the social context influence causes remarkable differences for the HS duration but not for the frequency of the HS for studied population. Indeed, the frequency of HS may depend on the psychological state of the persons and can also be related to personality traits, but this point was not studied in this article. Time to synchronize (for Greeting 0.28 ± 0.16 s and for Consolation 0.28 ± 0.18) presents a challenge for robot joint mechanical system control [2] and may need use special designed mechanical joints [20]. In our opinion, the control of this duration value will contribute to humanoid robot acceptance as a partner. The average value of strength of grip does not correlate with time to synchronize value and does not depend on the social context of the interaction. Taking into account the form of the grip force pattern (bigger in the begin of hand contact Fig.2), we can argue that it would be necessary to analyze the average strength of grip separately at two phases PhC and MS.
We think that the four phases representing the HS can facilitate its implementation for humanoid robot. Regarding to the results of this article, we propose some recommendations on parametrization of HS default values of robot controller. The first phase (SoH) can integrate the vocal greetings generated by the humanoid. The arm motion parameters during SoH play a significant role in the perception by human comfort, security, and the politeness of the robot's greeting gesture. The second phase (PhC) creates a unique topology of the gripping hands and causes the tuning of the motion parameters to achieve the synchrony of motion. Its duration must be limited to give the effect of the customary HS with a humanoid robot. Considering all these particularities, it is the most arduous task for the robot controller in providing an offensive movement synchrony. Using a variety of techniques (adaptation, learning, imitation, and prediction) in the shortest possible time to change the parameters of the motion of the robot arm is the third phase of the offensive when the arms are moving simultaneously. The third phase (MS) primarily characterises the human-like HS. Its duration depends on

the context of interaction and can reflect the personality traits or emotional and physiological state of the human being. The EoH phase, in our opinion, also has important meaning as the SoH phase.

5 Conclusion

This article focuses on the motion dynamics of an HS between humans to gain a better understanding of the nature of this phenomenon, and it shows that mutual synchronisation emerges in HS as well. Our work is one of the first that links the social context of a HS, multiple measurements of patterns, and an analysis of the phase synchrony of the hand acceleration during this human interpersonal action. For this purpose, we built a prototype instrumented glove device to measure the physical parameters during the HS. The acceleration of the HS was recorded with values of strength in the contact points of the hands for the two subjects using a pair of these gloves. These results will be interesting for HS motion planning in humanoid robotics in term of its duration and frequency of the length of the PhC phase and the MS phase. The new interactional skill of HS will expand the behavioural repertoire of a humanoid robot in the human environment. Because gender differences and personality traits play a significant role in HS, our future works will focus on experiments with more social contexts and more measures of arm and body motions and the psychophysical state. Our work is intended for a broad audience, and the critical issues of the duration and frequency of movements when shaking hands will be of particular interest to the field of psychology. Researchers in the field of humanoid robotics can also use the results of our work in physical interactions between human and robots. Although humanoid robotics is developing, there is still a need for new designs of controllers and actuators capable of giving robots movements more fluidity and compliance able to make them still more trusted and still more accepted by humans.

Compliance with Ethical Standards: The authors declare that they have no conflict of interest. This study was partially funded by French Embassy in Ukraine and French National Research Agency (ANR-09-CORD-014 INTERACT).

Acknowledgements We thank Eric Wajnberg for reading the manuscript and his help in statistical analysis. Artem Melnyk thanks professor Philippe Gaussier for the series of fruitful discussion about synchrony phenomena, Olga Kieffer and Dr. Alain Coulbois for support and contribution to the manuscript. The authors also wish to thank all the participants for their cooperation.

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